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TECHNICAL INNOVATION

Application of 3-D printing (rapid prototyping) for creating physical models of pediatric orthopedic disorders

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Abstract Three-dimensional printing called rapid prototyping, a technology that is used to create physical models based on a 3-D computer representation, is now commercially available and can be created from CT or MRI datasets. This technical innovation paper reviews the specific requirements and steps necessary to apply biomedical 3-D printing of pediatric musculoskeletal disorders. We discuss its role for the radiologist, orthopedist and patient.

Keywords Biomedical three-dimensional printing · Rapid prototyping · Computed tomography · Magnetic resonance imaging · Orthopedic disorders · Physical models · Pediatric

Introduction

Three-dimensional printing, also known as “additive manufacturing” and “rapid prototyping,” a technology that uses a 3-D computer representation to create solid objects from a feedstock material, has been available for nearly 30 years [1]. Three-dimensional print models for orthopedic conditions can improve understanding of anatomy and pathology by way of tactile and visual experience for both the surgeon and patient to complement images displayed on a computer monitor.

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The accuracy of the 3-D print is, of course, dependent on the contrast in the parent image, and also on the technical capabilities of the printer. A high contrast-to-noise ratio enables clear segmentation of the anatomy to be reconstructed. Musculoskeletal radiologic images lend themselves well to this technique because of the high conspicuity of ossified structures within the surrounding soft tissue. The purpose of this technical innovation paper is to describe the computer hardware and 3-D printer technical requirements as well as discuss clinical applications of 3-D print technology for pediatric musculoskeletal disorders.

Description

The 3-D printing field uses a vocabulary wherein words and acronyms that have specific meanings within the 3-D printing field have other meanings in other fields. For readers wishing to stay abreast of the most recent jargon of the field, a live glossary of 3-D printing terms is available at http://reprap.org/wiki/Glossary.

Printer selection

Current 3-D printing devices use a range of technologies, depending on the throughput requirements and spatial dimensions of the output. Consumer devices have a spatial limit of about 20 cm×20 cm×20 cm. Low-throughput devices take minutes to hours for a print and use a thermoplastic wire feedstock and an extrusion head that lays down a 0.1− to 0.5-mm thread in a raster pattern, layer by layer, to compose the desired 3-D shape. The melted thread in a given layer adheres to the previously deposited layer. As the print cools, the thermoplastic material hardens and sets the shape.

Higher-throughput devices use a powder sintering technique, applying confocal lasers to locally heat the powder bed [1]. They can typically print a complex shape at least an order of magnitude faster than the extrusion technique. These devices are capable of using higher strength and melting-point feedstocks, including metals. The technique is particularly efficient for high-value materials because waste is eliminated; the technique is of great utility in making titanium parts, a high-value material that is notoriously difficult to machine by conventional subtractive methods.

In this technical innovation paper, we restrict our attention to low-throughput print methods that create a small number (usually 1 or 2, rarely higher) of copies of the selected anatomy. Such models are useful for visualizing the anatomy of interest as a physical object for use in surgical templates and simulation as well as patient education. Larger numbers of models are rarely necessary for these purposes. We therefore focus our attention on the thermoplastic wire extrusion device class. Within this class, a wide range of printer options are available. The parameters that differentiate the devices in this class include:

(1) Printable volume. This defines the maximum dimension of the print in each of the three principal directions.
(2) Number of heads. Most printers can accommodate one feedstock, and an increasing number of devices can hold 2, 3 or more feedstocks. The "heads" or extrusion nozzles can each be individually optimized for the feedstock they deliver. They can be used for different colors or completely different materials.
(3) Spatial resolution. Contemporary 3-D printers have a filament thickness of about 0.1 mm. In practice, because of the vibrations originating in the motion of the heads themselves, the spatial resolution achievable rarely reaches this limit and is usually about 0.5 mm. Instruments with careful vibration suppression can achieve higher resolutions.

Among these low-throughput printers, costs vary quite significantly. High-end systems such as those marketed by Stratasys (Eden Prairie, MN) and 3D Systems (Rock Hill, SC) can easily reach $50,000 to $100,000. These systems are characterized by multiple print heads, vibration isolation (and consequently improved spatial resolution), more precise temperature control (and therefore less distortion upon cooling) and a wider range of feedstock possibilities. Low-end printers, such as those marketed by MakerBot Industries (Brooklyn, NY), are also available.

In our laboratory we use a Replicator model printer, a low-end consumer device manufactured by MakerBot that sells for less than $2,000 (Fig. 1). The printer has two heads and comes with ReplicatorG v.0037 software for printer control. Communication with the printer is done using the USB interface, or through the network. The software is also capable of generating an output file that can be transferred to the printer on a standalone device such as a SanDisk memory card (Milpitas, CA).

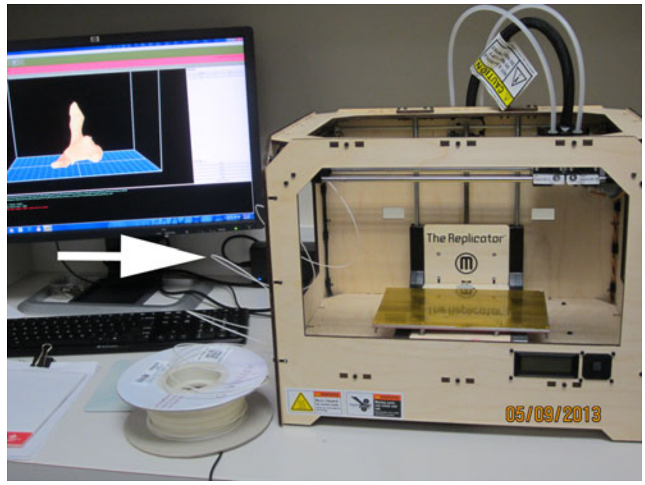

Fig. 1 A low-end 3-D printer made by MakerBot (Brooklyn, NY). Acrylonitrile butadiene styrene filament feedstock that is 1.75 mm in diameter (*arrow*) is the material used for 3-D print generation in this model printer

Material parameters

Numerous plastics have been used as feedstocks in 3-D printing, based on the desired end application. Poly-lactic acid (PLA) and starch-derived polymers are typically used for biocompatible applications. For most solid printing applications, the material of choice is acrylonitrile butadiene styrene. In our laboratory we use clear, natural (off-white) or black acrylonitrile butadiene styrene filament feedstock, 1.75 mm in diameter (Fig. 1).

Software and pre-processing

Before being loaded into the ReplicatorG software, a radiologic image needs to be converted into the standard surface description language (STL) format. In our laboratory, data for each case is transferred from the hospital PACS using the DICOM file format. The bones in the anatomical region of interest are segmented with 3D Slicer 4.1.1 (free software that can be downloaded from http://www.slicer.org) using the module "EMsegmenter without atlas." Any obvious errors in automated segmentation are manually corrected. This segmented volume is then converted to STL using the module "ModelMaker" with default settings. Inspection and correction of the modeled 3-D surface is done with MeshLab v. 1.2.3-64bit (downloadable at http://meshlab.sourceforge.net). Generally, three types of corrections are required in all models: (1) unifying duplicated verticals, deleting edges that are represented more than once in the model, (2) unifying duplicated faces, deleting faces that are represented more than once in the model and (3) removing isolated pieces that are obviously artifactual. An example of this process in action is shown in Fig. 2, from a patient with deformity related to coxa vara and

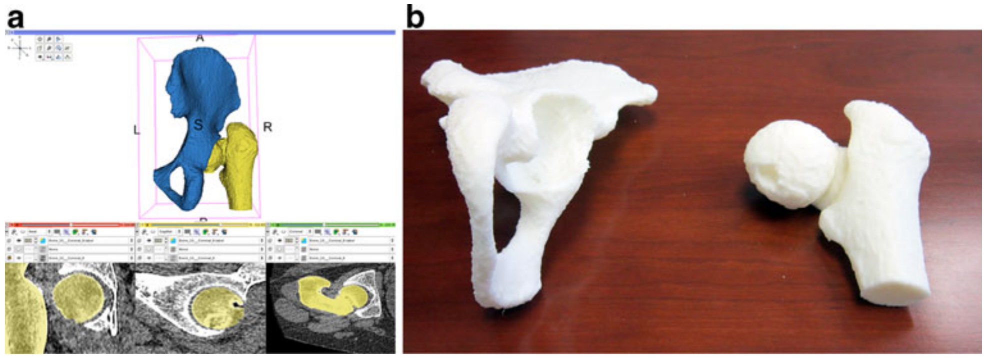

Fig. 2 Model of coxa vara in a 16-year-old boy. **a** Lower panels: segmentation of the DICOM images in Slicer. Upper panel: volume-rendered segmented geometry after conversion of CT DICOM data to standard surface description language (STL) format. **b** Three-dimensional print of the coxa vara deformity

slipped capital femoral epiphyses. The software is straightforward to use, and any technologist with a grasp of 3-D image processing can easily be trained to run the software.

Model orientation and external support

The 3-D printing process starts at the base of the shape to be printed, laying down the base on the printer plate, and building upward from the base. For simple models (e.g., a pyramid), the base is the largest cross-sectional area of the model, and all subsequent layers, being smaller and axially aligned, are supported completely by the lower layers. Such shapes are generally described as concave to the base. For more complex shapes, usually convex to the base, such as a sphere, the base is smaller than subsequent layers, which consequently have no underlying support, causing distortions in the shape upon printing. It is therefore important to orient the model for printing such that the incidence of overhangs or cantilevered portions is minimized. It is generally not possible to eliminate them altogether, and this is remedied by introducing a “raft support” below such cantilevered elements. Upon completion of the print, this support is then manually trimmed, freeing the parent shape. This raft support is usually made with a sparse parallel pattern so it is easy to distinguish from the parent shape while trimming. The ReplicatorG software (MakerBot, Brooklyn, NY) has an automated feature to add these supports, and in our laboratory we use it in its default setting (external supporting material). Alternatively, the support raft can be printed using the second head and in a different material from the primary printed object.

To conserve material, increase printing speed, and decrease cooling time, it is important to minimize the amount of completely solid material in the print. Most objects are adequately represented by a hollow shell, although some honeycombed filling within the shape is useful for structural integrity and overall rigidity. In cases where a surgeon might cut the print to simulate a surgery, filling of the object is also necessary to preserve the shape after the cut is completed. The ReplicatorG software provides a single, simple parameter to control the filling: the percentage filled. At 100%, it prints a completely solid object, and at 0%, it prints the shell alone. In our laboratory, we use 5% as the default. This provides a honeycomb interior that provides excellent strength and structural integrity even after a physical cut is made. Figure 3 shows the printing of the tarsal bones, with external supporting material for cantilevered elements.

Printer parameters

For a given feedstock the *linear velocity* and *temperature* of the extrusion control the majority of the performance characteristics. At high head temperatures, the fluidity of the feedstock plastic is higher, potentially allowing better defect filling in the print. However, the higher temperature requires longer cool-down times after completion of the print (about 1 h). At these high temperatures, the model may be exposed to unbalanced gravitational forces before it has totally hardened, and has the

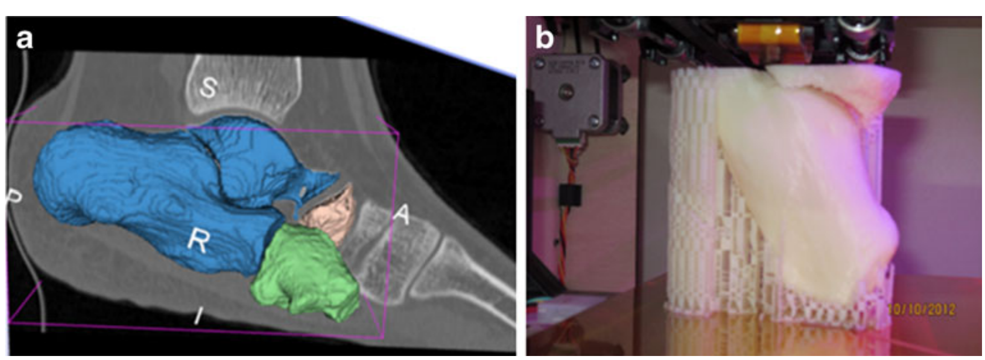

Fig. 3 Printing support network. **a** Sagittal volume-rendered CT image of the ankle. **b** Corresponding 3-D print being processed by the 3-D printer. Note the parallel under the printed object, necessary to support cantilevered parts during printing. The parallel or longs strips is trimmed off after printing to complete the process

potential to be distorted by gravity or handling before final finishing. Similarly, extrusion-head linear velocity has an effect on deposited material: the higher the velocity, the more likely the filament will be interrupted while printing. Such defects are often covered up by subsequent layers, which results in an overall weakening of the printed object. However, when present on superficial layers, they are visible and represent an inaccuracy in the printed shape. Similarly, too slow a head velocity leads to material pooling, causing false “plugs” to appear in the print. Another parameter that is important for larger complex shapes is the temperature of the platen on which the print rests while in process. If it is too hot, it prevents quick hardening of the print. If it is too cold, it causes thermal stresses. In our laboratory, we use a feed rate of 40 mm/s matched by a travel rate of 40 mm/s, a layer thickness of 0.29 mm, a print temperature of 235°C and a platen temperature of 110°C as our default parameters and adjust these values on a case-by-case basis.

Discussion

Three-dimensional printers used to be rather expensive and were only accessible to a few sophisticated machine shops as recently as 10 years ago, primarily because the computer power required to process these sophisticated datasets was only available on high-end workstations.

The technology has attracted much attention in the recent past, fueled by a combination of circumstances: (1) Rapidly increasing computing power has made the production of 3-D computer representations of complex objects feasible even on entry-level personal computers. (2) Rapidly falling costs of the embedded systems within the printers themselves have reduced the costs of 3-D printers to consumer-accessible levels. (3) A small number of extreme projects have caught the attention of the popular media. For example in 2013 Dutch architect Janjaap Ruijssenaars announced his intention to 3-D print an entire house. A student entrepreneur at the University of Texas published plans for a completely 3-D printed gun. It was downloaded more than 100,000 times before being removed at the request of the U.S. Department of Homeland Security. (4) The U.S. president mentioned in a recent State of the Union speech the establishment of a 3-D printing research hub, the National Additive Manufacturing Innovation Institute in Youngstown, OH.

This combination of notoriety and falling costs has driven a marked interest in the technology at the consumer level, in turn further contributing to reducing costs. A consumer printer can be acquired for as little as $2,000, while professional-grade instruments can be acquired for about $10,000. In fact, a widely cited Gartner Group report [2] predicted that enterprise class 3-D printers would be selling for less than $2,000 by 2016.

Three-dimensional printing offers an alternative methodology to view complex 3-D shapes from a 2-D CT or MRI dataset. This technique has been applied for defining craniofacial deformities and rheumatologic cervical spine deformities, for orthopedic biomechanical testing of the knee, for cardiac applications and for forensic imaging [3–8].

A 3-D print at a 1:1 scale provides a tactile and visual experience. Cooke et al. [9] studied the way humans use visuo-haptic inputs to understand solid objects and concluded that using both modes of input leads to less ambiguity in the understanding the shape of the object. A natural extension is therefore to use radiologic images coupled with 3-D printing to reconstruct three-dimensional models of anatomy. Such models have advantages over conventional volume rendering on a 3-D workstation for surgical planning and patient education. They make it easy for non-radiologists (surgeons, patients) to physically hold in their hands a model of the anatomy of interest and use visuo-haptic inputs to better understand the condition to be treated. The 3-D prints could be used during the discussion and surgical consenting process so that the patient and family understand the gravity of the medical or surgical condition. Surgeons might refine or even experiment with different techniques on a 1:1 scale print model of the actual orthopedic deformity in a no-stress environment prior to definitive surgical correction (Fig. 4).

Three-dimensional printing has a host of pediatric orthopedic applications for congenital and acquired disorders including but not limited to the evaluation of pediatric developmental hip deformities (Fig. 4), post-traumatic physeal bars (Fig. 5), 3-D nature of Blount disease (Fig. 6) and subtalar coalitions (Fig. 7). Three-dimensional printing does not supplant the diagnostic interpretation of 2-D CT and MRI datasets but should be used to complement imaging interpretation. We anticipate that the utility of 3-D printing will be further enhanced when non-experienced observers are involved, for example patients and professionals without formal radiology training and experience.

More experience with 3-D print datasets will be necessary to help refine which orthopedic pathologies might benefit from the addition of a 3-D print. Anecdotally, 3-D prints of osteo-articular alignment disorders have most often been requested by our orthopedists. The orthopedists have noted that these models add clinical value because they can help them understand how to correct the alignment disorder from a 3-D perspective that usually cannot be fully appreciated on a computer monitor. A patient with a complex proximal femoral deformity from healing Perthes disease serves as an example (Fig. 4). Reconstruction in such a patient requires an understanding of the precise location and size of the deformity of the femoral head and neck and of the degree of hip flexion when it comes into contact with the acetabular rim. Additionally the femoral neck-shaft angle, relative neck length, trochanteric height, and femoral version might all be deranged. A 3-D print allows for the ability to study the deformity and not only plan the surgery including the exact placement of implants, but also simulate the procedure to

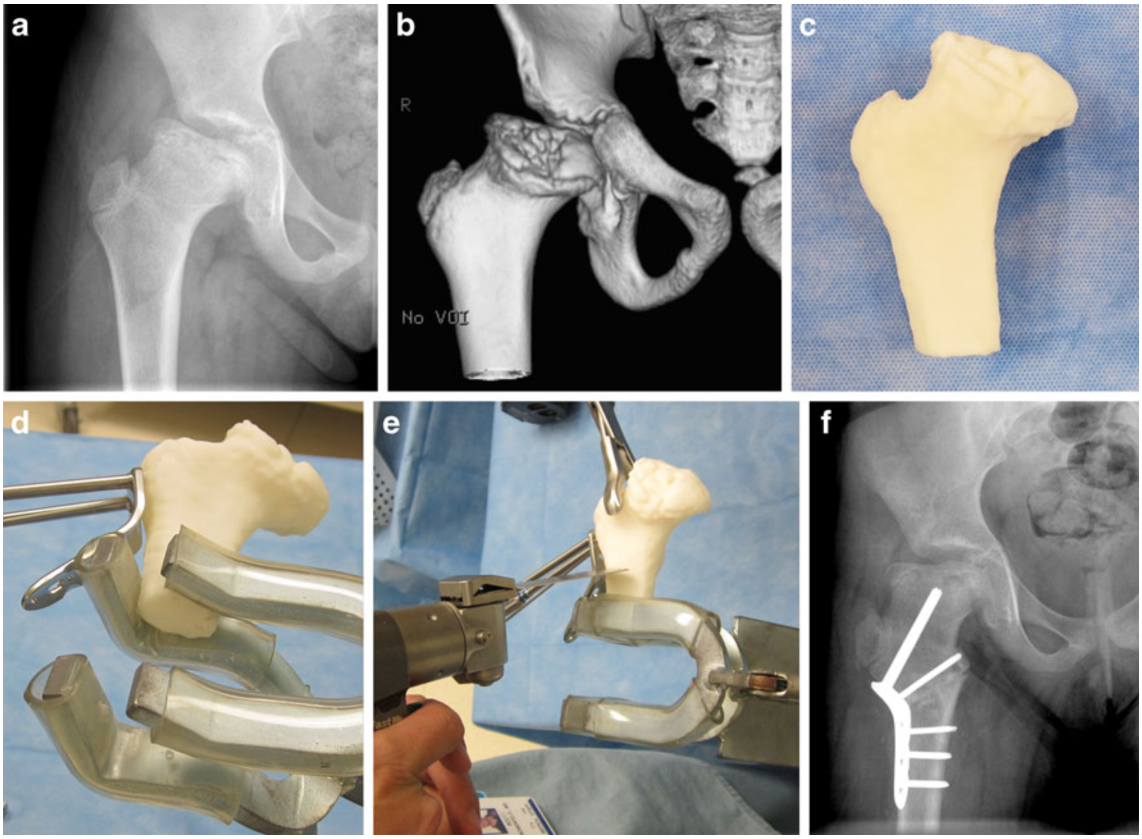

Fig. 4 Three-dimensional models of Perthes disease in a 10-year-old girl. **a** Radiograph, (**b**) 3-D maximum-intensity projection and (**c**) 3-D print from CT data show healing Herring class 3 Perthes disease. **d**, **e** Three-dimensional prints can be used to simulate proposed surgical corrections. **f** Radiograph after subtrochanteric valgus osteotomy of the right femur to align the more medially located spherical component of the femoral head to the weight-bearing portion of the hip joint

confirm that the deformity will be properly corrected and motion adequately restored. Such planning principles can be applied to any complex orthopedic deformity where precision of implant placement is vital to success of correction. The ability to practice the correction on a model before performing the actual surgery might decrease the rate of improper implant placement, resulting in less adjustment time in the operating room, shorter operative time and ultimately better patient outcomes. Three-dimensional prints of other conditions such as physeal bars (Fig. 5) and coalitions (Fig. 7) may have more limited clinical utility for both the radiologist and orthopedists and in those cases the 3-D prints serve mainly as a patient and trainee education tool.

Disadvantages of 3-D printing include: (1) There are limitations caused by spatial resolution of the relatively coarse (0.1–0.5 mm) filaments used in commercial, commodity printers such as the instrument used in this work. However,

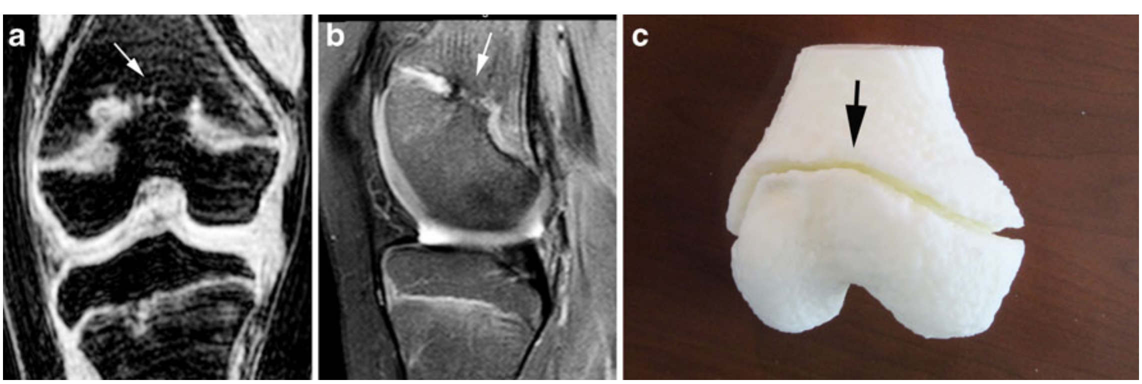

Fig. 5 Central physeal bar of the distal femur in a 12-year-old boy. **a** coronal gradient recalled echo and (**b**) sagittal T2-W fat saturated MR image demonstrates a central phyesal bar (*arrow*). **c** 3-D print demonstrate physeal cupping deformity (*arrow*). The 3D print does not show the physeal bar because of its central location

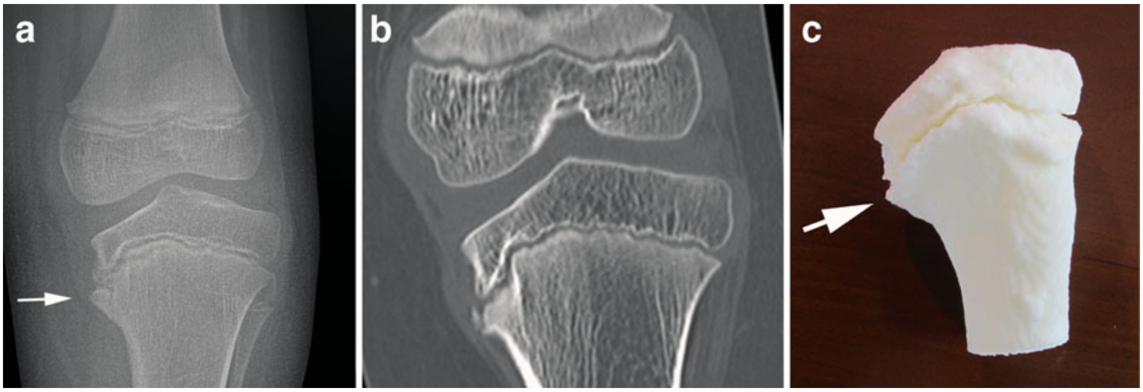

Fig. 6 Model of Blount disease in an 8-year-old girl. **a** Radiograph, (**b**) CT coronal reconstruction and (**c**) 3-D print demonstrate metaphyseal beaking (*arrow*), medial physeal irregularity and diminished epiphyseal height

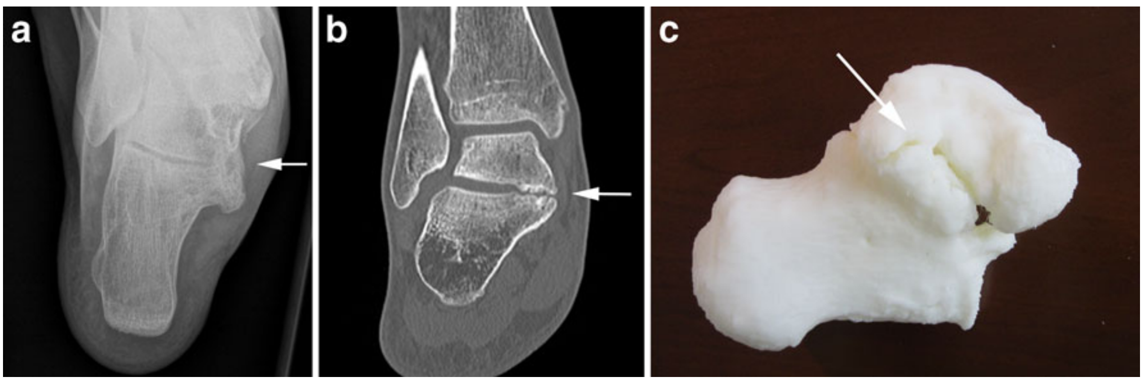

Fig. 7 Fibrous subtalar coalition in a 17-year-old girl. **a** Harris view, (**b**) coronal reformatted CT and (**c**) 3-D print demonstrate a fibrous coalition of the middle subtalar joint (*arrows*)

this resolution is comparable to that of the images themselves (usually 0.5–1 mm). (2) Difficulty in observing internal architecture with a 3-D model, such as a central physeal bar hidden by the metaphysis and epiphysis (Fig. 5). (3) The cartilage and soft-tissue support structures are not typically included with 3-D prints because of their complexity. Consequently, 3-D prints do not comprehensively illustrate all biomechanical elements of a joint and should not be interpreted in isolation without the original orthogonal CT or MRI datasets.

In summary, 3-D printing is a commercially available and inexpensive tool that has significant application in pediatric musculoskeletal disorders. Three-dimensional printing supplements but does not replace interpretation of 2-D CT and MRI datasets with conventional post-processing. The value of 3-D printing is the additional tactile and visual experience it affords to both the orthopedist and patient in understanding congenital and acquired pediatric musculoskeletal disorders and its potential to aid in treatment planning and simulation.

Conflicts of interest None

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